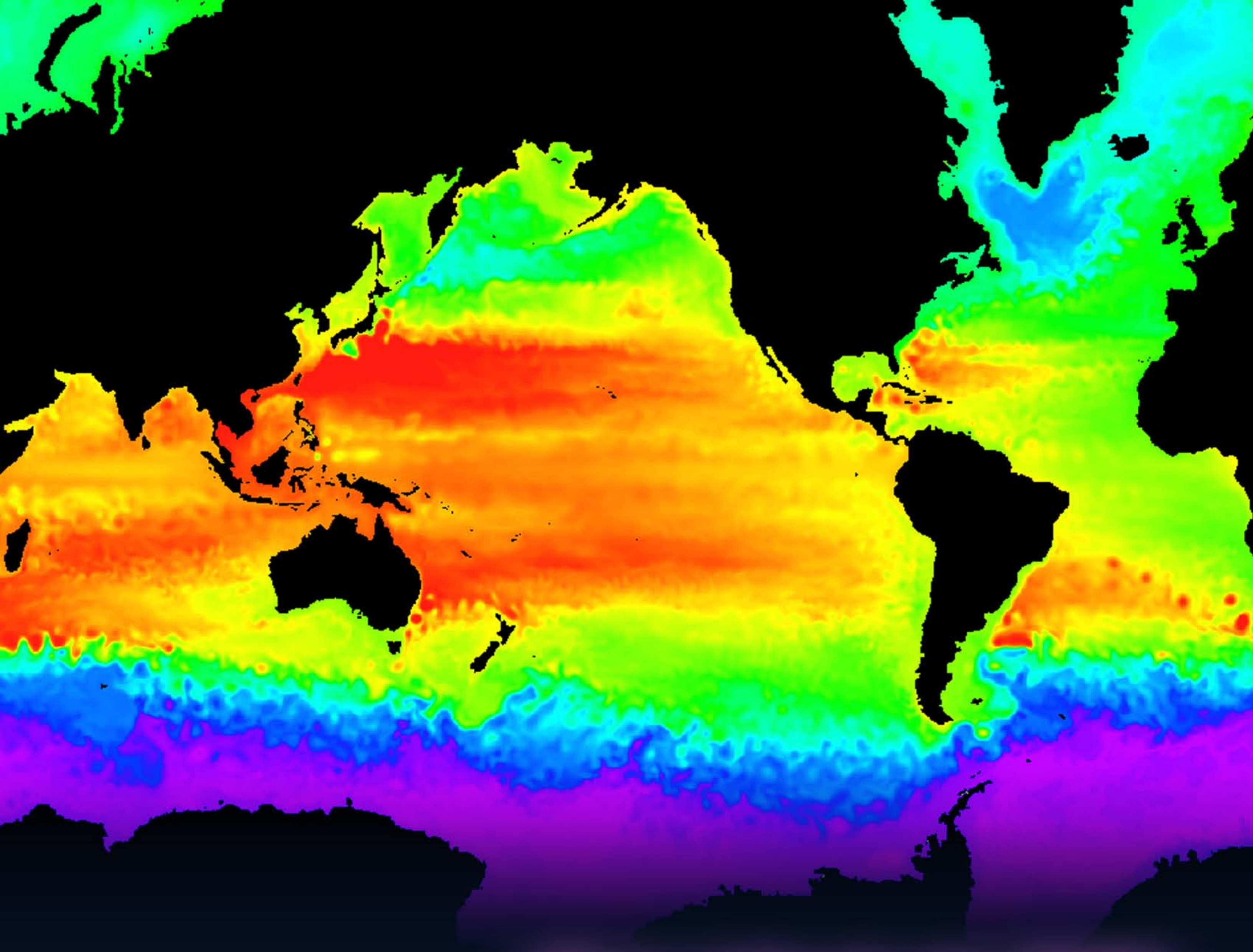

CLIMATE

Energy and Environment Compendium

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CLIMATE

Energy and Environment Compendium

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LALP-04-026

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Climate Research at Los Alamos National Laboratory

Climate variability presents a range of challenges to the future well-being of society. The prospect of global warming due to increasing greenhouse gases will impact environmental cycles and energy planning in highly uncertain ways. Improving our understanding of these impacts and developing adaptation and mitigation strategies is a national problem that Los Alamos is addressing.

Sound energy policy requires an understanding of the primary external drivers that will impact the nation's energy future over the next 25 to 50 years. One of the principal impacts is from climate variability induced by both natural cycles and anthropogenic forcing. To prepare for this looming issue, the collective resources of the Department of Energy's national laboratories will be necessary to develop innovative strategies that can ensure the success of the DOE in its energy security mission.

Los Alamos has developed a full range of capabilities to address the problem of climate variability. The foundation of these capabilities resides in our world-renowned program in global ocean modeling. These ocean models are a primary component of the nation's foremost climate prediction system. Climate process models have also been developed at Los Alamos and implemented into our ocean models to investigate ocean carbon cycling. At the regional scale, Los Alamos has an ongoing effort that has made great strides in developing a comprehensive model to predict water resources within the upper Rio Grande Basin. The Laboratory also operates and maintains three climate monitoring sites in the Tropical Western Pacific for the DOE's Atmospheric Radiation Measurement (ARM) program.

Current Scientific Challenges in Climate Research

Improved Prediction—Additional ocean and terrestrial data sources from remote sensors and climate monitoring stations are required to validate coupled global climate models that are undergoing continuous improvements to achieve higher resolution and more accurate representations of climate processes.

Regional Climate—It is necessary to understanding climate change impacts on human infrastructures and ecosystems over specific geographical regions where policy is implemented. Reducing the uncertainty in regional climate variability predictions is key to adapting to and mitigating climate change effects.

Aerosols—Anthropogenic aerosols are the most uncertain component of climate variability prediction due to their feedbacks on the radiation balance of the climate system. Recent research indicates aerosols may also be implicated in the suppression of hydrologic cycles over regions of the globe.

Decision Models—Achieving better understanding of global to regional climate variability and its feedbacks throughout the geophysical system will lead to improved forecasts and assessments. These can be developed into decision support systems that can determine climate change impacts on the human condition and help to reduce the costs of adaptation and mitigation.

Problem-Solving Capabilities in Climate Research

Los Alamos maintains and continues to develop climate-related research and development capabilities in the following areas:

Modeling and Simulation
- Global Ocean
- Parallel Ocean Program (PoP)
- Miami Isopycnal Ocean Model HYCOM/MICOM
- Sea Ice—CICE model
- Numerical and Gridding Methods
- Massively Parallel Computing Applications
- Regional Climate Modeling—RAMS/LADHS

Climate Processes—Modeling and Measurements
- Ocean Biogeochemistry
- Water Resources/Hydrology
- Atmospheric Aerosols
- Radiative Transfer
- Atmospheric Chemistry
- Terrestrial/Marine Ecosystems
- Wildfire Behavior
- Hurricane Intensity Prediction

Climate Monitoring
- ARM—Tropical Western Pacific climate stations
- Ecological monitoring of semi-arid landscapes
- FORTE/GPS—lightning data to global scales
- Image Analysis—GENIE software

Paleoclimate
- Isotopic correlation with dendrochronology
- Ecohydrology applications

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In addition to Los Alamos's extensive capabilities in modeling and monitoring the physical environment, the Laboratory is also recognized for its capability in energy infrastructure modeling for the Department of Energy and Department of Defense. These models require realistic inputs of economic and population dynamics in addition to data from a comprehensive model of the behavior of the future physical system. These inputs are used to drive realistic scenarios of energy demands. Combining our capabilities in understanding the physical, infrastructure, and economic environment can provide a unique capability to address future threats to energy security from climate variability and demographic shifts.

Climate, Ocean, and Sea Ice Modeling Project

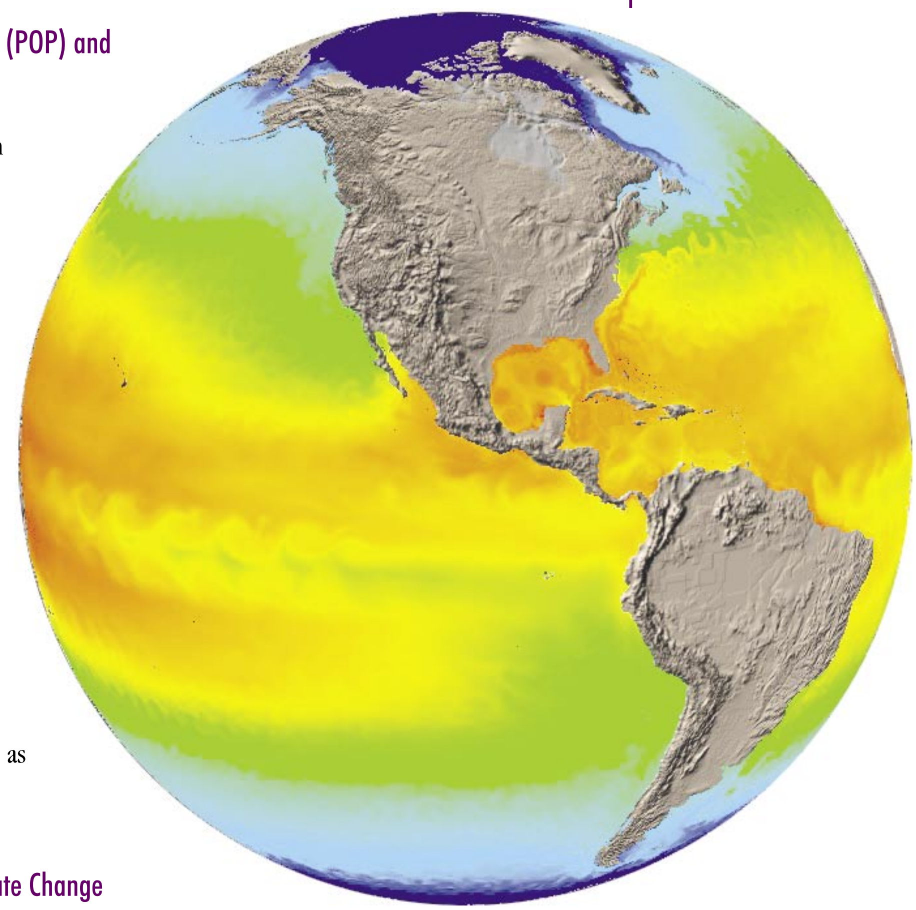
The Challenge: Understanding the Role of Oceans and Sea Ice in the Climate System

The primary mission of the Climate, Ocean, and Sea Ice Modeling (COSIM) project is to improve our understanding of the ocean and sea ice and their roles in the climate system. It has been designated by Los Alamos National Laboratory as a model development center under the Department of Energy Climate Change Prediction Program. In collaboration with other institutions, COSIM researchers have joined ocean and sea ice components with atmosphere and land components for fully coupled models of the Earth's climate system. The models are used for national and international climate assessments, including decadal-to-centennial climate change.

Los Alamos Innovation: Parallel Ocean Program (POP) and Sea Ice (CICE) Models

Developed at Los Alamos by a multidisciplinary team of physical scientists, applied mathematicians, and computer scientists, the POP and CICE models have been publicly released and used throughout the world's climate community. They also form the ocean and sea ice components of the Community Climate System Model (CCSM), a community modeling effort based at the National Center for Atmospheric Research.

In addition to these high-profile successes, the Laboratory's high-performance computing capabilities have enabled COSIM researchers to develop and validate physically and computationally advanced codes for simulating the circulation of the world's oceans, including the cryospheric component. Ultra-high resolution POP simulations of ocean circulation have also been performed and these simulations have been used to improve the understanding of the ocean and sea ice, as well as their role in the climate system.



Sea surface temperature from a high-resolution (1/10 degree) simulation of global ocean circulation using the POP model.

The Impact: Accurate Simulation of Global Climate Change Scenarios

The global modeling expertise and experience gained from the COSIM project and its participation in community modeling have resulted in the successful link of the wider global climate community with access to community data sets and other component models. The project has also provided valuable tools that can be used to directly simulate global change processes and scenarios. Data to drive other models, such as regional downscaling studies, have also been provided. In addition, the physical fidelity and computational performance of POP and CICE have continually been improved and have allowed for greatly enhanced ocean simulations for climate change scenarios.

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High-Resolution Ocean Simulations

The Challenge: Developing a High-Resolution Simulation of Ocean Circulation

The Los Alamos Parallel Ocean Program (POP) in applied environmental prediction has long been considered for use by the U.S. Navy for acquiring high-resolution simulations of ocean circulation. POP allows Los Alamos to provide simulations of the ocean's circulation at a very high resolution (1/10th degree grid spacing). This simulation would then be used as an initial condition for short time scale ocean atmosphere predictions in regions of strategic interest to the Navy.

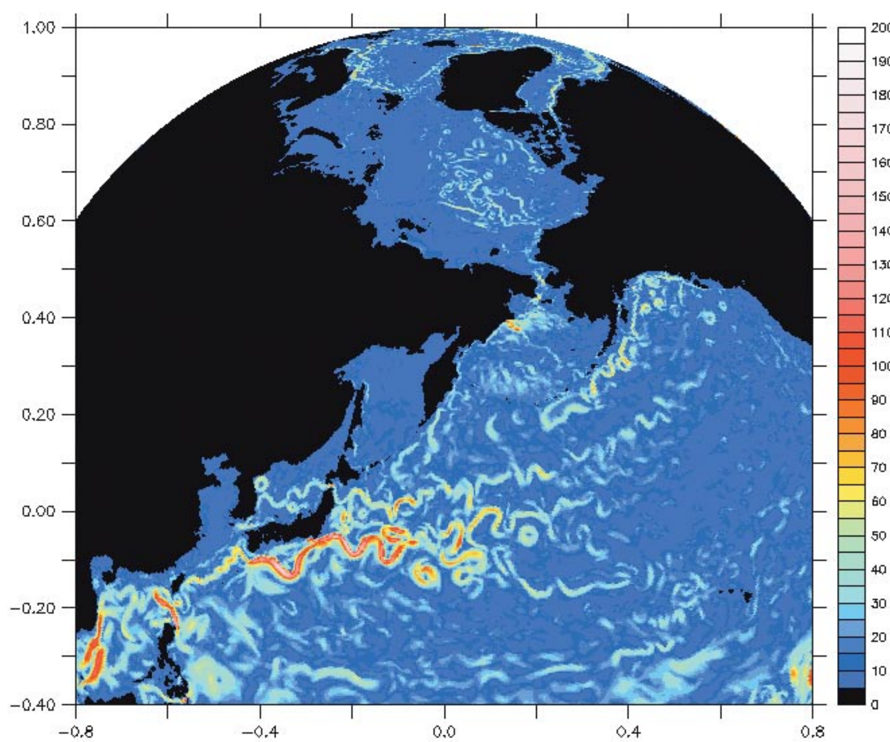
Los Alamos Innovation: High-Performance Computing for High-Resolution Simulations

Los Alamos National Laboratory's Climate, Ocean, and Sea Ice Modeling (COSIM) project is known for its use of high-performance computing to perform high-resolution simulations of ocean circulation. It is this expertise that has separated Los Alamos from other institutions and led to its selection by the U.S. Navy to perform ocean circulation simulation. This simulation was the largest ever attempted using a coupled model and fit successfully into the potential progression of runs. Preliminary results from this simulation have demonstrated that POP is capable of being used as a member of a predictive coupled model.

The Impact: Improved Ocean Models

Undertaking the ocean circulation simulation project has helped the COSIM project to improve ocean models, further augmenting the Laboratory's capabilities in modeling climate. It also reinforced Los Alamos's belief that high-resolution simulations play a crucial role in understanding ocean circulation. Such successes will allow the Laboratory to continue to perform these kinds of massive runs for a diverse clientele. This includes coupling with sea ice at high resolutions in order to create higher fidelity solutions in polar regions.

A snapshot of the current speed (cm/sec), at a depth of 15 meters, from a 1/10th degree POP ocean circulation simulation, reveals realistic features. Shown here is the meandering Kuroshio Current off Japan's East coast with its turbulent nature.



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Biogeochemistry

The Challenge: Anticipating Threats Posed by Climate Change

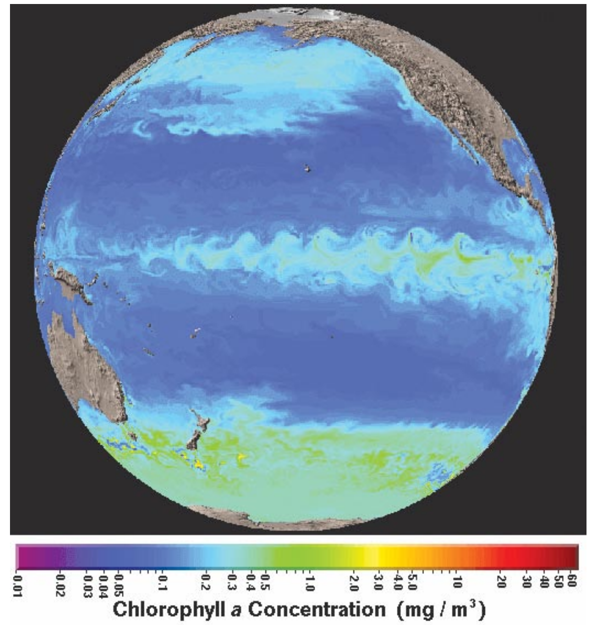
Current U.S. environmental policy emphasizes comprehending global change and developing technological solutions to the immense problems posed by greenhouse warming. The national climate science community and its Department of Energy component have responded to this by supporting detailed earth system modeling and simulation. These efforts include modeling of climate physics, basic elemental cycling within the coupled ocean atmosphere system, strategies for carbon management, and other aspects of global biogeochemistry.

Los Alamos Innovation: High-Resolution Ocean Biogeochemistry Modeling

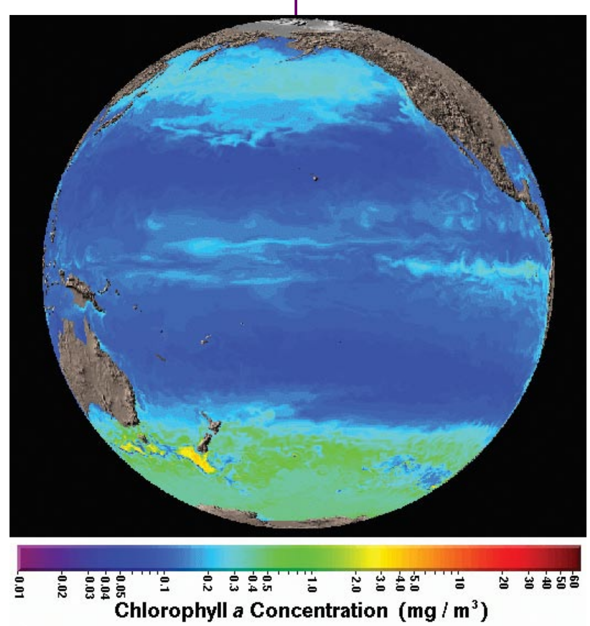
The Los Alamos ocean modeling team has successfully introduced biogeochemistry routines into its Ocean General Circulation Model (OGCM). Los Alamos's approach to ocean biogeochemistry modeling is unique in several crucial ways. Most importantly, the simulations are built into and based upon the fine mesh global general circulation models for which the Laboratory climate team has become well known. Biology and elemental cycling in the upper ocean are tightly coupled to vertical pumping by horizontal eddies at the 10 to 100 kilometer scale. Only Los Alamos's codes are capable of producing this sort of resolution while also supporting full biogeochemistry. The model has been used to study the impact of El Niño/La Niña events on marine ecosystems and to create detailed statistical simulations of the behavior of proposed iron fertilization of the oceans for carbon sequestration. Also included is the coupling of marine mixed layer trace gas mechanisms with processing by tropospheric chemistry modules and intercomparison of surface ocean ecodynamics models.

The Impact: Knowledge to Form a Marine Carbon Management Plan

Los Alamos's ocean biogeochemistry studies will allow researchers to investigate the coupling of Earth's climate and biogeochemical systems and to study possible linkages and feedbacks occurring between ocean physics, biology, and chemistry. The studies will further help clarify the costs, benefits, and environmental ramifications of marine carbon management plans. Further improvement of carbon cycling within the Community Climate System Model is also a primary goal of this effort.



Results from an eddy resolved simulation show the impact of El Niño/La Niña on the marine ecosystem: surface chlorophyll distribution in late 1996 (top figure, La Niña year), and late 1997 (bottom figure, full El Niño conditions).



Global Ocean Modeling with the Hybrid Coordinate Model (HYCOM)

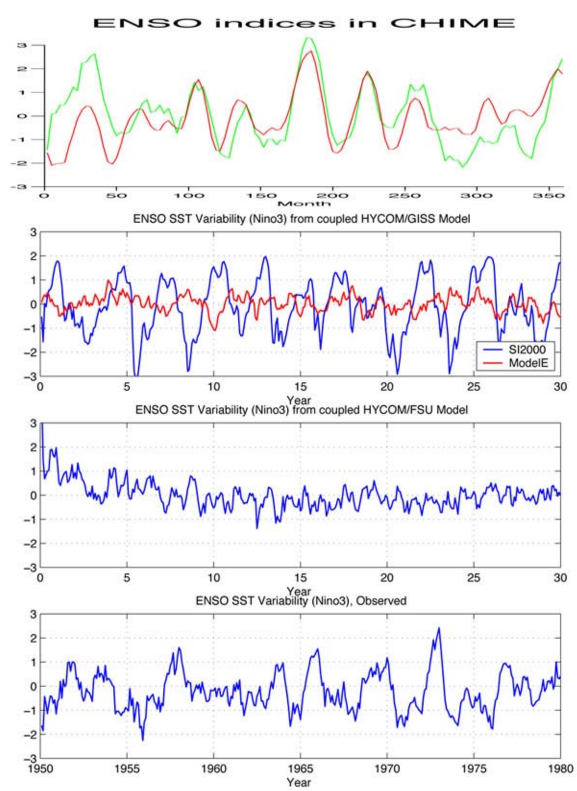
The Challenge: Reducing Uncertainty in Long-Term Climate Prediction

To reduce uncertainty in long-term climate prediction, the Intergovernmental Panel on Climate Change (IPCC) relies on multi-model ensemble forecasts made by pooling the world community's stock of climate models. However, the IPCC is well aware that, since these models were not developed independently of one another, "such an ensemble does not constitute an independent unbiased sampling of possible model formulations." Until recently, the climate model "gene pool" has been particularly sparse with respect to its oceanic component.

Los Alamos Innovation: Expanding the Ocean Model Base with Hybrid Coordinate Models

Responding to this situation, Los Alamos's Climate, Ocean, and Sea Ice Modeling (COSIM) team several years ago decided to broaden its ocean model base from one to four, essentially by adding an isopycnic-coordinate model, MICOM, to the in-house Cartesian coordinate model (the Parallel Ocean Program, or "POP") and by using both as the basis for developing so-called hybrid coordinate models. The principal design difference between Cartesian and isopycnic ocean models is that a Cartesian model treats depth as an independent variable and water density as a dependent variable, whereas an isopycnic model switches the role of the two. While the underlying dynamic principles are not affected by this switch, the differential equations describing the laws of fluid dynamics are noticeably different, particularly in their computer-solvable finite-differencing methods. Hybrid coordinate models (HYCOM's), viewed by many as an important and much-anticipated step toward the "ultimate" ocean model, attempt to combine the advantages of isopycnic models in the deep ocean (where water parcels move along density surfaces) and of Cartesian models in the surface mixed layer (where turbulent exchange processes are best modeled in a framework of constant-depth surfaces).

By providing three ocean model architectures, Los Alamos National Laboratory is unique among the world's climate research centers. This diversity has spawned within the COSIM team the development of diagnostic software allowing detailed, process-oriented intercomparisons of model results. Current process studies focus on the way our different models maintain the meridional overturning circulation (MOC) in the world ocean in response to changes in surface forcing (e.g., during global warming). The MOC is believed to be one of the more fragile links in the global heat distribution system, and our ability to predict the climate on multidecadal time scales depends critically on our models' abilities to mimic the natural variability of the MOC.



Thirty-year time series of El Niño-related sea surface temperature variability (°C) in HYCOM coupled to several atmospheric circulation models. Different colors indicate model runs based on different parameter choices. The large model-to-model variation in Niño3 amplitude is largely unexplained and the subject of intense research.

The Impact: More Accurate Climate Change Planning

Los Alamos's HYCOM/MICOM modeling efforts will

- Participate in the current round of IPCC assessments of the likely effect of CO_2 doubling on the earth's climate;
- Investigate the resiliency of the MOC during global warming and regional consequences of a possible breakdown;
- Simulate the carbon cycle with emphasis on enhancing oceanic CO_2 sequestration via iron fertilization; and
- Assess regional impacts of greenhouse-gas-induced global change.

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Collaborative Development of the Community Climate System Model

The Challenge: Developing a Community Climate System Model

Community Climate System Model (CCSM) developers at Los Alamos are working on software design, performance optimization and portability, and model development. The ultimate goal of the project is to enable the addition of atmospheric chemistry and ocean biogeochemistry to the coupled model. Under the DOE Scientific Discovery through Advanced Computing (SciDAC) program, an effort was funded for the collaborative development of CCSM for terascale computers. The SciDAC collaboration includes Los Alamos and five other DOE laboratories, the National Center for Atmospheric Research, and the NASA Data Assimilation Office.

A computer model of the Earth's climate system is made up of individual computer models for the four main components: the atmosphere, the global ocean, sea-ice in the polar regions, and the land surface. These components interact by passing information to each other through a "coupler." If atmospheric chemistry and ocean biogeochemistry are included, the carbon cycle of the Earth can be studied. Each of the component models is designed to run on multiple processors, and all components also run in parallel on different processor sets on a single massively parallel computer.

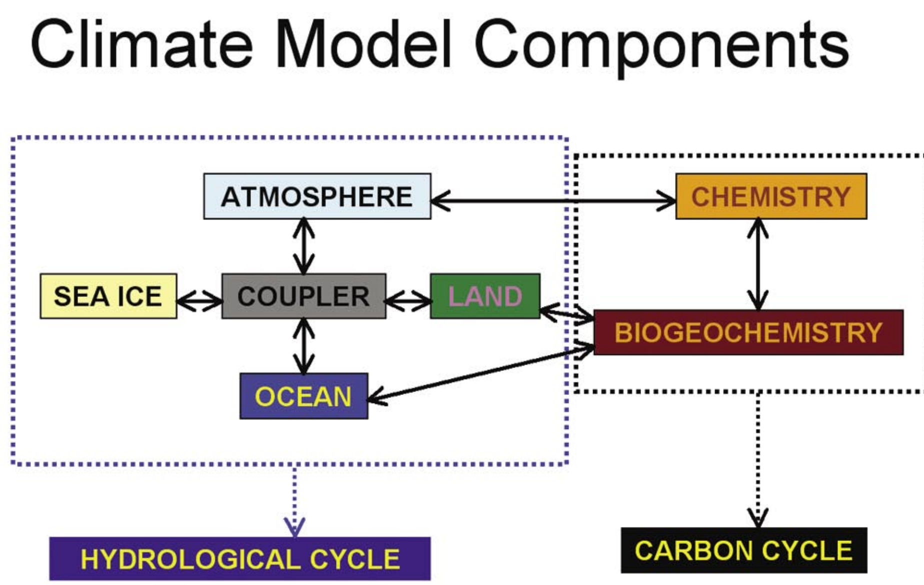
Los Alamos Innovation: Enhancing All Aspects of the CCSM

With expertise in high-performance computing and collaborative software development, Los Alamos's role in SciDAC has improved the Parallel Ocean Program (POP) and Sea Ice (CICE) models, which it originally developed and supplied to the project. Through the DOE Climate Change Prediction Program, SciDAC supplements work in Los Alamos's core funding.

Los Alamos's efforts have resulted in accelerating the development of a new Arbitrary Lagrangian-Eulerian vertical coordinate scheme in the POP ocean model and have added a new remapping transport scheme to the CICE model. The Laboratory's involvement has also enabled the design and integration of ocean biogeochemistry into the POP model and has focused on software process improvements in adopting a more formal design and testing process for the development of ocean and sea ice models.

The Impact: The Best Possible Model for Climate Change Studies

Current SciDAC efforts will advance work on the CCSM while providing collaborators, such as Los Alamos, with the best possible coupled climate model for use in climate change studies. Future work will create capabilities for performing carbon cycle modeling and permit the simulation of the full carbon cycle in coupled climate models in the biogeochemistry-atmospheric chemistry portion of this project.



Geodesic Quasi-Lagrangian Climate Model

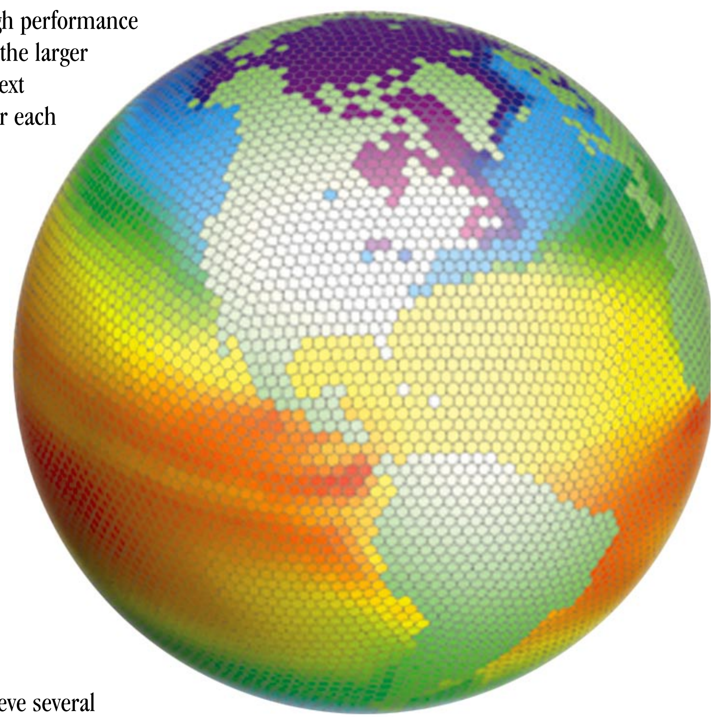
The Challenge: Predicting Climate Change on Long Time Scales

The Environmental Sciences Division of the Department of Energy has among its chief scientific objectives the development of a process to accurately predict climate change on decadal and longer time scales. The current phase of the DOE research effort is the Climate Change Prediction Program (CCPP). In support of the CCPP, Los Alamos is taking part in the Geodesic Quasi-Lagrangian Climate Model project. The project will develop a new model that is highly efficient for future high-performance computers as well as more accurate in its representation of physical reality and, therefore, will be more able to predict the future response of the climate system. This 5-year cooperative agreement is funded by the Scientific Discovery through Advanced Computing (SciDAC) program.

Los Alamos Innovation: Applying Existing Capabilities to a Geodesic Grid Model

Based on its demonstrated capabilities in developing ocean models for high performance computers, Los Alamos will provide the ocean and sea ice components of the larger coupled climate model. To the primary goal of this project—building a next generation global climate model using an almost uniform geodesic grid for each of the model's components—Los Alamos will contribute the following:

- Parallel Ocean Program (POP) code, which already serves as the ocean component in two of the nation's primary numerical climate models: the Community Climate System Model (CCSM) and the Parallel Climate Model (PCM);
- HYPOP model, which is a new hybrid vertical coordinate ocean model on a geodesic grid that has been developed over the past 2 years; and
- Geodesic grid models, which have provided the dynamical core algorithms for and assisted in the development of the new German Weather Service geodesic grid global weather forecast model and are currently in use in more than 20 countries.



An example of a geodesic grid with a color-coded plot distribution. The continents are depicted in white. This grid has 10,242 cells, each of which is about 240 km across. Twelve of the cells are pentagons; the rest are hexagons.

The Impact: Simplified Coupling of Models through a Universal Grid Geometry

With Laboratory contributions, the completed climate model will help relieve several computational difficulties by eliminating the polar singularities inherent in traditional latitude-longitude grids and simplify coupling of component models with a universal grid geometry for all models. The model will also allow for approximate Lagrangian treatment of vertical flow with hybrid vertical coordinates, except in the boundary layers at the Earth's surface, and provide higher computational efficiency on future generations of parallel supercomputers. It will also enable higher fidelity treatments of the atmosphere, ocean, sea ice, and land surface systems.

Earth System Modeling Framework

The Challenge: Developing Flexible Software Tools for Earth System Modeling

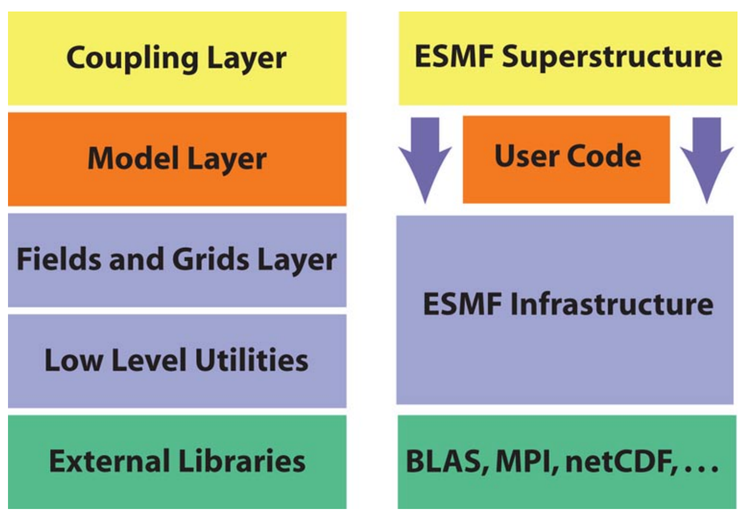
The need for further development of flexible software tools for use in Earth system modeling has become increasingly apparent in recent years. To address the issue of excessive time and resources being expended on this challenge, the NASA Earth Science Technology Office (ESTO) funded the Earth System Modeling Framework (ESMF) collaboration. This 3-year effort involves Earth scientists and computational experts from Los Alamos National Laboratory and nearly all of the other major modeling centers in the climate and weather forecast communities. The ESMF collaboration is developing a robust, flexible set of software tools that will respond to the computational needs of increasingly complex models and platforms.

Los Alamos Innovation: Remapping and Regridding to Couple Models

As the developers of the Spherical Coordinate Remapping and Interpolation Package (SCRIP), Los Alamos will provide the ESMF with expertise in remapping and regridding functionality, which is critical for coupling together models on different grids. The Laboratory will implement the framework in the Parallel Ocean Program (POP) and Sea Ice (CICE) models to ensure these codes can interoperate with other component models in the framework.

To address these complex challenges and goals, Los Alamos is

- Implementing a redesign of the SCRIP software to meet the requirements of the ESMF and continuing to improve its capabilities and flexibility with testing of additional ESMF components; and
- Incorporating framework elements into the POP and CICE models as they become available to ensure the models are compliant with the ESMF.



The Impact: A Common Software Framework for a Diverse Community of Users

This diverse collaboration of proven expertise will ensure a framework will be implemented across a broad range of institutions to address the complex needs of the entire community. In addition, the development of a software interface specification will allow groups at all participating institutions and in all disciplines to generate interoperable software components. The result will be enhanced and improved data communication, model component coupling and sequencing, time management, and parameter specification.

The ESMF effort creates opportunities for Los Alamos-developed component models to be adopted by other modeling efforts. The Laboratory achieves greater flexibility in its response to new initiatives or global change issues, and its ability to incorporate new aspects of the climate system, currently not included in coupled models, is enhanced. Finally, ESMF permits Los Alamos to interoperate with other components and collaborate with a wider community to customize applications with the best components.

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NASA Computation Technologies Project:
Applying the Earth System Modeling Framework to the El Niño-Southern Oscillation

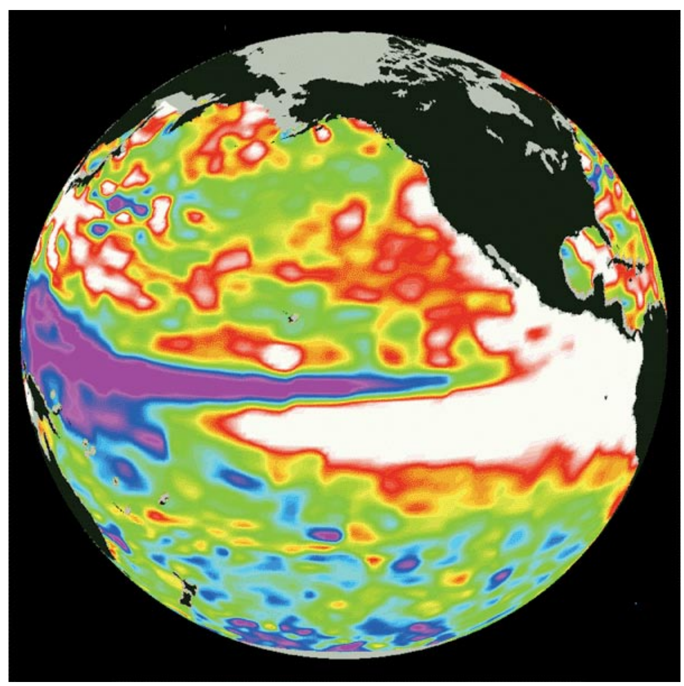
The Challenge: Understanding the Global Climate Effects of the El Niño-Southern Oscillation

Developing an Earth System Modeling Framework (ESMF) is the focus of three of the current cooperative agreements of the Computational Technologies (CT) Project in the NASA Earth Science Technology Office. As part of a separate CT cooperative agreement headed by the University of California, Los Angeles (UCLA), Los Alamos will be using ESMF to couple its HYPOP ocean and CICE sea ice model with the UCLA atmospheric general circulation model as an early validation of ESMF functionality and efficiency. This undertaking will enhance coupled model simulations of the El Niño-Southern Oscillation and its global effects on climate.

From measurements made by the U.S./French TOPEX/Poseidon satellite, this Pacific Ocean image shows sea surface height relative to normal conditions. The volume of warm surface water (white) represents the core of 1997/98's El Niño in the eastern Pacific Ocean. Green indicates normal; purple indicates cool.

Los Alamos Innovation: Seamless Coupling of Model Components

Based on its demonstrated capabilities in developing ocean and sea ice models for high-performance computers, Los Alamos was asked to provide the ocean and sea ice components of the larger coupled climate model. The Laboratory responded by developing a new hybrid vertical coordinate ocean model, known as HYPOP. This model provides an ideal opportunity for demonstrating ESMF ability to interchange model components in a largely seamless manner. Interpretation of vast quantities of observational data will be enhanced while the process of swapping and comparing alternative scientific approaches from varying research groups to improve the models' fidelity and predictive capabilities will be simplified.



The Impact: Realistic Simulations of Natural Phenomena

Los Alamos will now engage in an important university collaboration and a key NASA initiative to develop a software infrastructure for the climate modeling community. With Laboratory contributions, the ESMF will provide more realistic simulations of natural phenomena and eliminate time-consuming reprogramming by handling all communications in coupled climate models and enabling them to run on a variety of supercomputer architectures.

National Ocean Partnership Program (NOPP) Paradigm Project

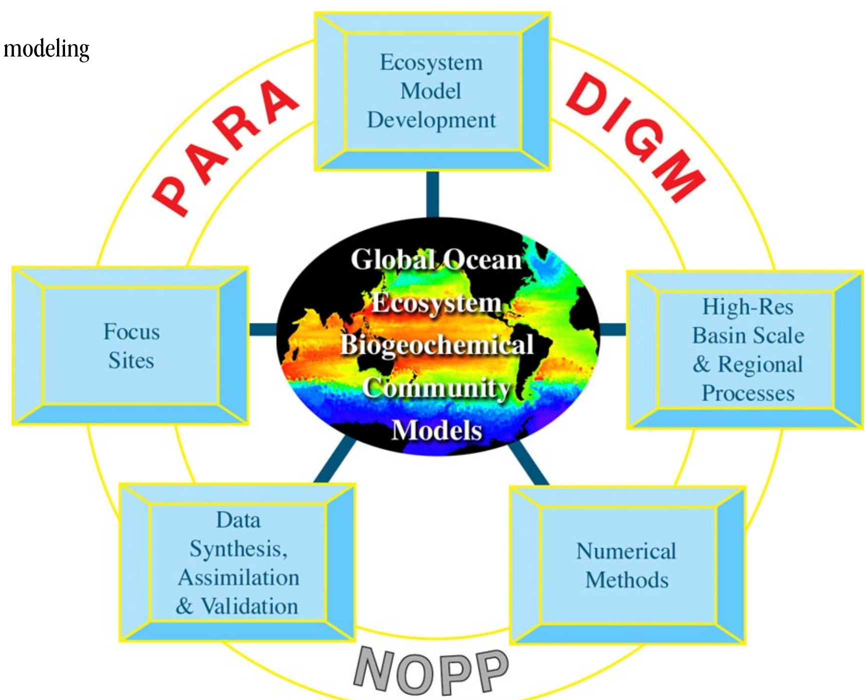
The Challenge: Including Marine Ecosystems in the Global Carbon Cycle Model

Modeling the full Earth system—which includes the ocean, sea ice, atmosphere, and biosphere—is an extremely complicated challenge that has not yet been met. An accurate model of the global carbon cycle must include marine ecosystems and other geochemical processes that naturally occur in the global climate system. Such a model would provide a greater understanding of ocean biogeochemistry to facilitate global change prediction. To address this issue, the National Ocean Partnership Program (NOPP) has sought the help of Los Alamos and 14 other institutions in order to implement the PARADIGM project.

Los Alamos Innovation: Advanced Biogeochemical Modeling

Los Alamos has accepted the challenge of providing the key research component for the community ocean circulation model and providing support for the development of the Parallel Ocean Program (POP) of the PARADIGM project. The Laboratory is employing its unique capabilities in high-performance computing and modeling and simulation to perform high-resolution ocean simulations with an imbedded ecosystem model for POP. This complicated ecosystem model describes the growth, decay, transfer, and evolution of almost 20 different species, ranging from 3 types of phytoplankton to dimethyl sulfide to carbon dioxide.

Used by other members of PARADIGM, the biogeochemical modeling performed by Los Alamos will result in the development of the next generation of ecosystem models and improve understanding of the carbon cycle while advancing knowledge of the environmental effects of greenhouse gases.



The Impact: A Fully Coupled Earth System Model

As a component of the Coupled Climate System Model (CCSM) at the National Center for Atmospheric Research, POP will be used in the future for fully coupled carbon cycle simulations which will further our understanding of global change. Los Alamos's contributions to POP have provided a valuable resource for carbon cycle research and global change prediction. The Lab's biogeochemical component of the POP project will bring the scientific community one step closer to a fully coupled Earth system model.

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Tropical Climate Monitoring

The Challenge: Monitoring Global Climate

The Department of Energy's Atmospheric Radiation Measurement (ARM) Program has selected Los Alamos National Laboratory to manage its climate monitoring stations in the Tropical Western Pacific (TWP). Climate monitoring in the TWP is important for the following reasons:

- The TWP consistently has the warmest sea surface temperatures on the planet and is referred to as the Pacific "warm pool";
- The warm pool supplies heat and moisture to the atmosphere above it, resulting in the formation of deep convective cloud systems which, in turn, produce high altitude cirrus clouds that spread out over much of the region;
- These cloud systems regulate the amount of solar energy reaching the surface of the earth and the amount of the earth's heat energy that can escape to space.

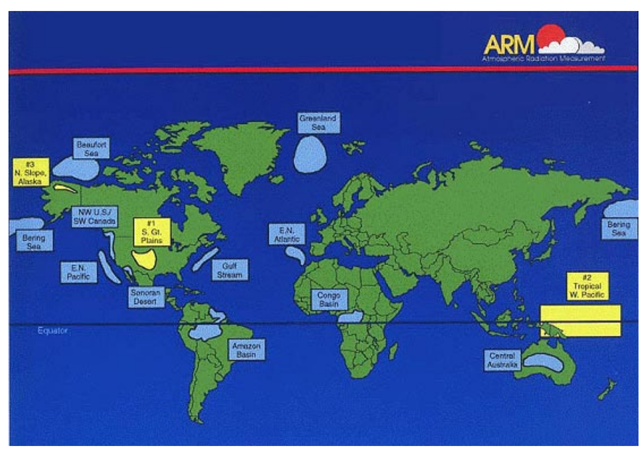
Los Alamos National Laboratory recently began to manage the deployment, maintenance, and calibration of a new ARM Mobile Facility. The purpose of the mobile facility is to extend climate monitoring to regions of the globe that are not well characterized by the stations ARM presently maintains in the TWP, the Southern Great Plains, and the North Slope of Alaska.

Los Alamos Innovation: Managing Climate Monitoring Stations

The sites in the TWP locale include the islands of Nauru and Manus, Papua New Guinea, and a new facility built last year in Darwin, Australia. In addition to instrument calibration/maintenance and data quality assurance for ARM sites, Los Alamos's responsibilities include

- Foreign contract management,
- Local observer and visitor safety awareness,
- Site security,
- Power and communications (which can be undependable),
- Intermittent transportation, shipping, and import customs,
- Local government policies, and
- Cultural sensitivities and land ownership issues.

Atmospheric Radiation Measurement (ARM) sites—established stations in yellow and possible locations for the ARM mobile facility in blue.



The Impact: Producing High Quality and Continuous Data

The operation of the sites in the TWP region and the new mobile facility is designed to address the core mission of the ARM Program which is to

- Improve the performance of General Circulation Models (GCM's) used for climate research and prediction by improving the treatment of radiation transfer under clear sky, overcast, and broken cloud conditions; and
- Improve the parameterization of the properties and life cycle of clouds in the GCM's.

Los Alamos National Laboratory will maintain the infrastructure required to produce high quality and continuous data from a variety of sensors. These sensors range from *in situ* point measurements, through balloon-borne profiles, to complex remote sensing active and passive instrumentation. The data at the sites are also used to study important climate related phenomena such as the Southern Oscillation and as ground truth for satellite observations. The satellite observations range from continuous geostationary satellites, through relatively standard orbiting satellites such as AVHRR and MODIS, to special satellites such as the DOE Multispectral Thermal Imaging (MTI) satellite.

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Resolving the Aerosol-Climate-Water Problem by Integrating Observations and Models

The Challenge: Predicting the Effects of Aerosols on Health, Climate, and Water

A pressing question confronting society is how particle emissions from human activity affect our health, global climate, and water supplies. The current scientific assessment of this aerosol problem faces some fundamental challenges:

1. Aerosol effects on climate are the most uncertain element in climate assessment. The problem is so severe that we do not know whether net effects of anthropogenic emissions (greenhouse gases and aerosols) are warming or cooling our climate.
2. Aerosols have been implicated in suppressed rainfall, persistent monsoon failures, and prolonged drought. If confirmed, such perturbations of the Earth's hydrological cycle could outweigh present concerns about global warming.

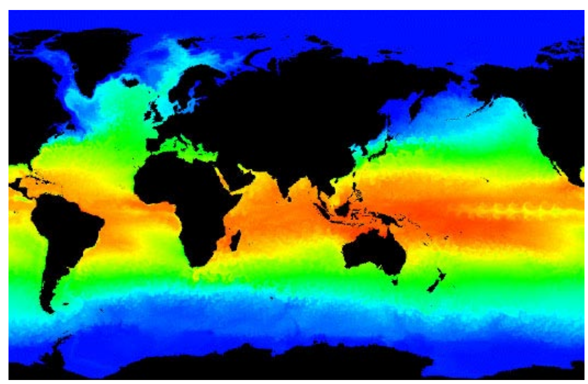
Quantifying the role of aerosols poses a scientific challenge because of their complex composition, range of lifetimes, ability to absorb and/or scatter solar and terrestrial radiation, and effect on cloud properties.

Above: Department of Energy's MultiThermal Imager (MTI) is used to examine clouds, aerosols, water, and surface properties.

Below: Simulated ocean temperatures in a Los Alamos ocean model.

Los Alamos Innovation: Linking Satellite Observations and Laboratory Experiments

Los Alamos is poised to tackle the aerosol problem with an integrated approach that couples observations, models, and experiments to capture processes and assimilate data in coupled-climate and atmospheric-transport models. We are linking three pillar capabilities at Los Alamos—remote sensing science, ocean-atmosphere modeling, and laboratory aerosol diagnostics—and collaborating with key external institutions (NASA, NCAR, and Scripps) to quantify the role of aerosols in climate change and to develop predictive tools to assess their long-range transport and impact on water resources.



The Impact: Rapid Aerosol Forecasting Tools

Los Alamos's efforts will provide predictive assessments of the impacts of aerosols on climate and water resources and will enable the development of next generation data assimilation methods for rapid aerosol forecasting tools.

Regional Climate Modeling

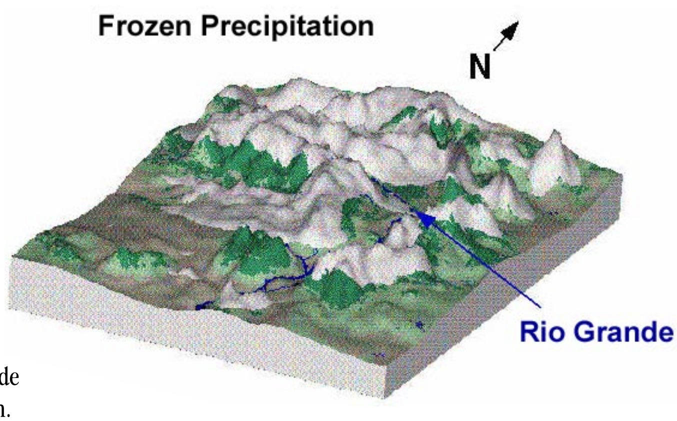
The Challenge: Predicting Climate Change Effects on a Regional Scale

The headwaters of the Rio Grande are located in the San Juan Mountains of southwestern Colorado and the upper portions of the river are fed primarily by snowmelt from winter storms. In contrast, the lower portions of the river accumulate runoff from thunderstorms of the summer monsoon season. Consequently, the waters of the Rio Grande are strongly influenced by regional climate and could be vulnerable to climate change. Since precipitation and runoff in arid regions are low and highly variable, improved knowledge of the climate and hydrology is essential for optimal management of water resources in the Rio Grande basin and other arid regions of the world. It is important to understand the entire hydrologic cycle and to be able to explore the potential effects of increased water use and of changes in global and regional climate. Global climate models (GCMs) utilize grids that are too coarse to resolve changes in regional climate and the predictions for a particular region vary depending on which global model is used. Therefore, the results of global climate predictions need to be downscaled to extrapolate the global predictions to regional relevance. Regional climate models can dynamically downscale global climate predictions to a more usable resolution.

Los Alamos Innovation: An Interactive System of Atmosphere, Surface, and Groundwater Models

The research reported here is part of a larger project that is coupling a suite of environmental models to simulate the hydrologic cycle within river basins. These models include the Regional Atmospheric Modeling System (RAMS) which provides meteorological variables and precipitation to land surface hydrology models. To downscale global climate predictions, RAMS can use GCM-predicted meteorological fields to initialize and nudge the model fields. The surface hydrology model partitions the precipitation into evaporation, transpiration, soil water storage, surface runoff, and subsurface recharge. The surface hydrology component is being updated to include the TIN-based Real-time Integrated Basin Simulator (tRIBS), developed at the Massachusetts Institute of Technology (MIT). The runoff is collected within a simple river channel model and the Finite Element Heat and Mass (FEHM) subsurface model is linked to the land surface and river flow model components to simulate saturated and unsaturated flow and changes in aquifer levels. Our goal is to produce a fully interactive system of atmospheric, surface hydrology, river, and groundwater models to allow water and energy feedbacks throughout the system.

Spatial distribution of frozen precipitation (white) over the RAMS third grid, which includes the upper Rio Grande Basin to Albuquerque, NM. The green shades represent the topography, from lighter shades at lower elevations to darker shades at higher elevations.



The Impact: Evaluating Changes in Regional Extremes

This approach will allow us to examine changes in regional extremes for properties such as precipitation and temperature that cannot be obtained from global climate model simulations because of their coarse resolution. Los Alamos's regional climate simulations can provide planning tools for water resource managers and planners in regions of concern.

Distributed Hydrological System for Modeling Water Resources

The Challenge: Meeting Increasing Demands for Water Resources

With limited supplies and increasing demands for water resources, especially in arid and semi-arid regions, it is becoming increasingly important to understand the workings of the hydrologic cycle within river basins. A thorough understanding of typical precipitation, runoff, and groundwater and the nature of the their variability is vital for planning the best use of these water resources. In the long term, all aspects of the hydrologic cycle affect the availability of water and it is therefore important to explore the entire cycle in order to understand the potential effects of increased water use and of changes in the regional climate. Allocations of scarce natural resources like water can be based on detailed computational models of complex natural-human systems.

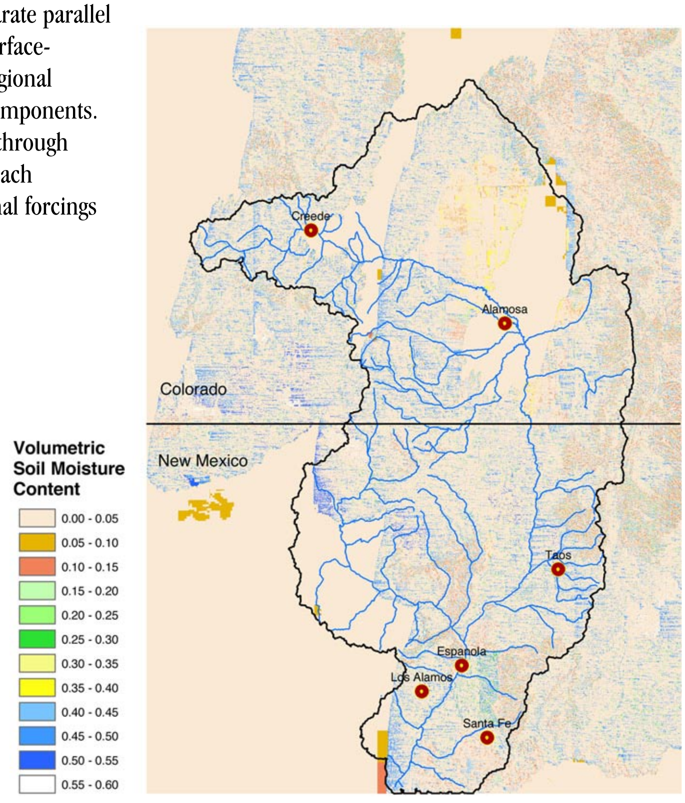
Los Alamos Innovation: Coupling Existing Models to Form a Single Virtual Watershed Model

To simulate water resources, Los Alamos researchers are coupling a series of existing and previously tested models in a single virtual watershed model that addresses the multitude of physical processes and temporal and spatial scales that are important. The Los Alamos Distributed Hydrologic System (LADHS) currently emphasizes natural processes, but components can be extended to include such anthropogenic processes as municipal, industrial, and agricultural demands. LADHS is composed of four interacting components: a regional atmospheric model, a land surface hydrology model, a subsurface hydrology model, and a river routing model. The system is embedded in the Parallel Applications Workspace, which is a software infrastructure for connecting separate parallel applications within a multi-component model. Integrated atmosphere-land surface-groundwater models like LADHS provide a more realistic assessment of the regional water balance than separate models can by including feedback between the components. For example, boundary conditions from global climate models can propagate through the virtual watershed and the effects of interactions can then be evaluated in each component. Many of these components are nonlinear and the effects of external forcings are not readily predictable.

The Impact: Effective Management of Water Resources

Los Alamos's virtual watershed model, the Los Alamos Distributed Hydrologic System, retains the essential physics of all elements of a regional hydrosphere and allows feedback between them. At the highest level of description, LADHS functionality reflects exchanges of mass and energy between physical elements of the regional hydrosphere. Results of initial simulations of the water balance between the land surface and atmosphere in the upper Rio Grande basin illustrate the promise of this approach. Compared to real watersheds, virtual watersheds are cheap to produce and allow experimentation. They are flexible enough to accommodate novel boundary conditions like land use change and increased climate variability. Decision-makers can use virtual watersheds to evaluate the risks of management alternatives once uncertainties have been quantified.

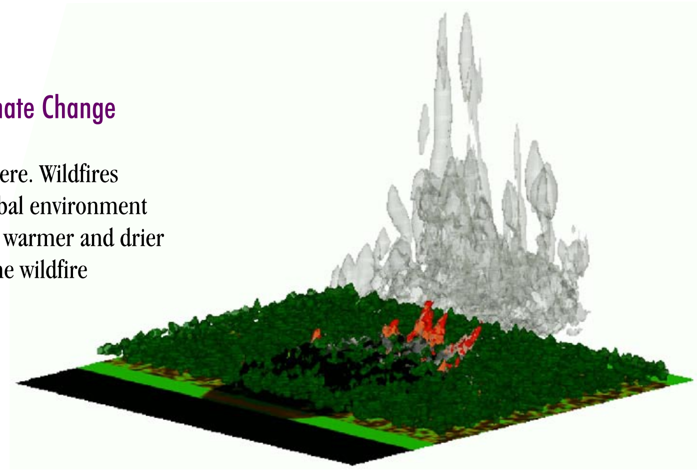
Soil moisture field—the black outline depicts the boundaries of the upper Rio Grande basin.



Climate Change and Wildfire Emissions

The Challenge: Understanding the Effects of Wildfire Emissions on Climate Change

Wildfire emissions are a major source of carbon and aerosols in the atmosphere. Wildfires are local to regional scale phenomena that have the potential to affect the global environment through atmospheric transport processes. Climate change scenarios describe warmer and drier environments in various areas around the globe that can lead to more extreme wildfire behavior and their associated emissions. At present, the impact of evolving environmental conditions on fire emissions is highly uncertain, due to a lack of data and simulation tools that can adequately describe complex fire behavior and chemistry.



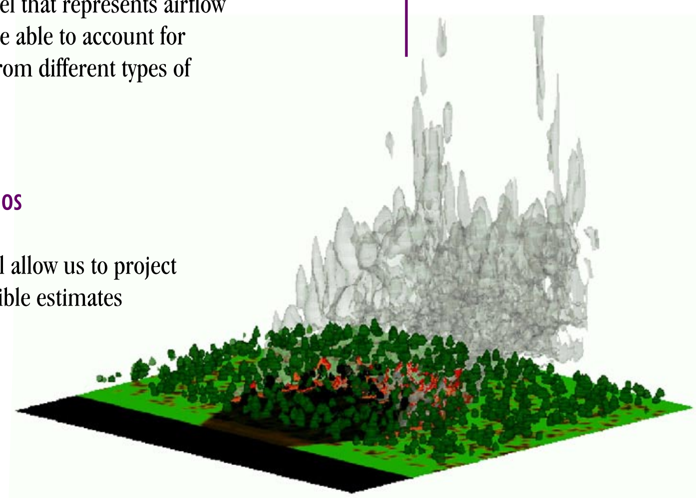
Wildfire simulation with FIRETEC in a dense (above) and less dense (below) forest stand showing flame intensity (red) and fire emissions (gray).

Los Alamos Innovation: A Physics-Based Wildfire Model

Over the past eight years, Los Alamos has developed a unique physics-based fire behavior model, HIGRAD/FIRETEC, that can begin to provide answers to fire emissions questions for better understanding of global climate change problems. HIGRAD/FIRETEC is the first physics-based, three-dimensional (3-D) computer code designed to simulate the constantly changing, interactive relationship between fire and its environment. It does so by representing the coupled interaction between fire, fuels, atmosphere, and topography on a landscape scale (hundreds or thousands of meters). HIGRAD/FIRETEC combines physics models that represent combustion, heat transfer, aerodynamic drag, and turbulence with a computational fluid-dynamics model that represents airflow and its adjustments to terrain and vegetation structure. The model will also be able to account for differences in the combustion, aerosol production, and emissions resulting from different types of fuels.

The Impact: Credible Estimates of Wildfires for Climate Change Scenarios

With some additional modifications, the HIGRAD/FIRETEC modeling suite will allow us to project greenhouse gases from wildfires of various fuel types and begin to make credible estimates of total greenhouse gas emissions from wildfires in climate change scenarios, taking into account statistically projected changes in numbers of wildfires worldwide due to changing temperature, moisture, and ecosystem health.



Climate Change and Ecosystem Dynamics

The Challenge: Understanding the Complex link Between Climate Change and Vegetation and Ecosystem Dynamics

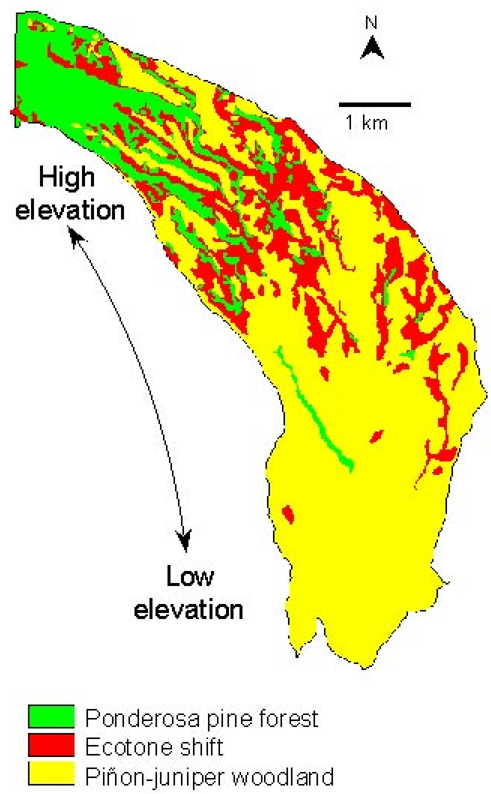
Climate is a key driver of vegetation dynamics and associated ecosystem changes. Changes in vegetation and ecosystem processes can also have important effects on climate and weather patterns. This interrelationship between climate and vegetation pattern/ecosystem properties is particularly pronounced in dryland environments, where water is so intimately tied to energy and carbon budgets. Researchers at Los Alamos National Laboratory are focusing on how water, energy, and carbon are affected and/or affect vegetation patterns and dynamics.

Los Alamos Innovation: Increasing Understanding of Ecosystem Processes

Studies of piñon-juniper woodlands and ponderosa pine forests at Los Alamos have significantly increased our understanding of ecosystems processes. Results of these studies include the following:

1. Quantification of the most rapid landscape scale response of an ecotone (a boundary between two ecosystems) documented to date in response to climate. During the 1950's drought, the ponderosa pine forest/piñon-juniper woodland ecotone shifted more than 2 km in less than 5 years. These results have important implications for assessments of ecosystem responses to climate variability and change.
2. Quantification in a piñon-juniper woodland of spatial heterogeneity in near-ground solar radiation, soil temperature, soil water content, snow cover, runoff, and erosion. This is the most intensely instrumented piñon-juniper woodland plot in existence.
3. Development of a model for transitions from low rates of runoff and erosion to high rates of runoff and erosion.
4. Development of a conceptual model relating both horizontal and vertical heterogeneity in soil moisture to plant community composition and dynamic responses to climate and land use.
5. Demonstration that interflow (shallow subsurface flow) in a semiarid ponderosa pine forest is a substantial part of the water budget. This is the first demonstration of the importance of this process in a semiarid environment.
6. Development of a spatially explicit ray-tracing model of solar radiation that has been used to quantify general trends in the spatial distribution of solar radiation as a function of changes in the proportions and patterns of woody plants.

Tree stand changes In Bandelier National Monument, New Mexico during the 1950's drought.



The Impact: Predicting the Interrelationships Between Climate and Vegetation

Los Alamos National Laboratory's data sets and modeling capabilities in ecology provide critical assets necessary to address emerging climate problems. In particular, through extensive field research we have developed many unique data sets and models that are central to evaluating the predictive interrelationships between climate and vegetation.

Paleoclimate Records and Climate Change in the Southwest

The Challenge: Examining Past Climate Cycles to Predict Future Water Availability

Understanding climate cycles that control the hydrologic cycle is the key to predicting future water availability. While instrumental records of climate and weather patterns only extend back approximately 100 years, proxy records of climate for hundreds of thousands of years can be reconstructed from tree rings, corals, ice cores, peat bogs, and speleotherms. Los Alamos is taking part in a pilot project funded by the University of California Institute of Geophysics and Planetary Physics to examine climate records contained in peat bogs from sites in the Jemez Mountains of North Central New Mexico.

Los Alamos Innovation: Applying Isotopic Expertise to Study the Environmental Record

The project will draw upon Laboratory capabilities in water and carbon research as it builds on previous work by Northern Arizona University, where research expertise in traditional paleo-environmental techniques has revealed significant climate variability in the semi-arid southwest. The state-of-the-art facilities and history in isotopic studies at Los Alamos provide technical expertise in light stable isotope environmental reconstruction and dating techniques that include both optically stimulated luminescence and uranium-series dating.

The Impact: Predicting the Occurrence and Magnitude of Future Droughts

With future climate change affecting water availability for agriculture and energy production as well as for industrial and household use, this study will focus on reconstructing a 10,000 year record of climate/drought variability in mountainous regions of the semi-arid southwest that can then be analyzed for underlying periodicities. The study will also help to determine if anthropogenic effects have changed the periodicities of phenomena such as the Pacific Decadal Oscillation, which results in long-term drought in the southwest. Ultimately, this work will provide climate time series that will be analyzed in terms of drought frequency, allowing prediction of future drought timing and magnitude. This work will also form the basis of future Los Alamos efforts to couple observational/experimental science with global change modeling efforts to address national issues of energy security, water security, wildfire risk, and environmental sustainability.

Ancient lake sediments in the Valles Caldera.

Warming Trends and Water Resources

The Challenge: Adapting to Rising Temperatures and Resulting Hydrological Changes

Warming trends have become apparent in the last forty years and are expected to accelerate in the 21st century. Current models also predict evaporation of more water vapor into the lower atmosphere. In regions with most of the world's population, societies will probably have to adapt not only to significant temperature rises, but also to profound hydrologic changes and increasingly intense and frequent convective storms. These storms cause most flash floods and all large hail, microburst winds, lightning, and tornadoes. In addition to generating severe weather, convective storms play two key roles in the climate system. First, they are the principal vertical transport path for water and latent heat between the lower and upper troposphere. This is key to the Walker and Hadley cells of low-latitude heat transport. Second, robust convective storms that overshoot the tropopause ("penetrative convection") inject cloud ice into the normally dessicated stratosphere. Stratospheric ice alters the radiative balance (via the visible albedo) and also serves as a host substrate for trace-gas heterogeneous chemistry (e.g., the sink for stratospheric ozone).

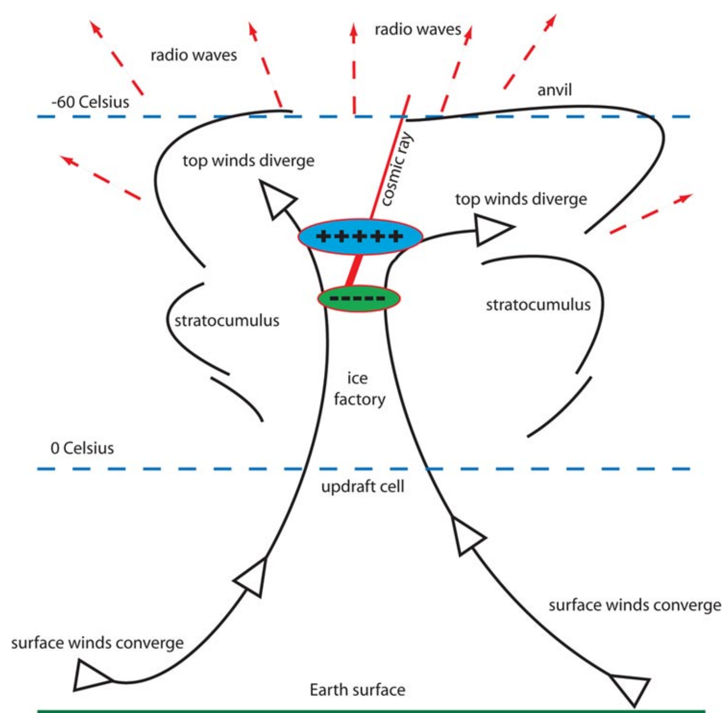
Los Alamos Innovation: Locating and Characterizing Storms by Analyzing Their Radio Emissions

During the 1970's, NASA Goddard scientists discovered spectacular radio emissions from convective storms. These radio emissions were approximately 100 times more intense than those ordinarily associated with lightning. Later, in the 90's, Los Alamos National Laboratory participated in the development of satellite platforms, ALEXIS and FORTE, which showed that these radio signals were the most likely weather-associated radio signals to be observable from space. The FORTE satellite, launched in 1997, performed simultaneous radio and optical observations of lightning and demonstrated that the pulses are unassociated with detectable luminous signals; that is, the intense radio pulses are "dark lightning." Moreover, the radio pulses are not the signatures of conventional electrical breakdown of the air, although such breakdown can be instigated by whatever causes the pulse. Indeed, conventional breakdown is sometimes observed to occur after one of the bright pulses is emitted. Detection of these radio pulses from storms indicates the location and severity of significant tropospheric convection. Detection can be done from the GPS constellation by instruments that Los Alamos National Laboratory designs, builds, and maintains.

The Impact: Environmental Security

The U.S. government is aggressively emphasizing a national strategy of adaptation to climate change. Significant new support is planned for an adaptive (as opposed to a preventive) national climate program. Los Alamos National Laboratory's capabilities are perfectly aligned with this strategy of adaptation which aims to employ sophisticated sensor networks to provide timely and accurate warning of developing outbreaks of severe weather that have the potential to harm people, communities, aviation, and facilities. To succeed, the nation urgently needs scientific and technical breakthroughs in detection and tracking of nascent, severe, convective storms, globally and in real time.

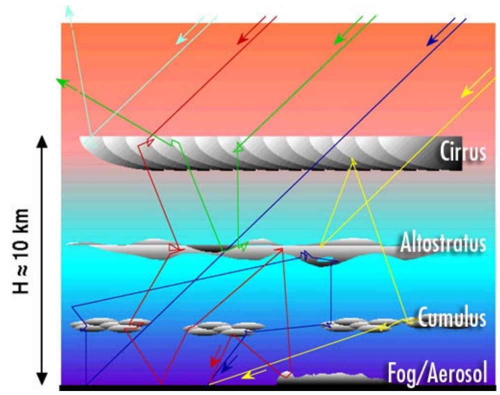
An intense updraft generates layers of positive and negative charge high in the updraft cell. Incident cosmic ray (solid red line) instigates relativistic-avalanche breakdown (heavy line) in region of high electric field between charge layers. Radio-wave emissions provide means for real-time satellite retrieval of 3-D position of breakdown. Between the 0 and -60 Celsius isotherms is the region of mixed-phase hydrometeors (graupel, ice crystals, supercooled droplets). This mixed-phase condition requires a sustained and intense (>15 m/s) updraft with copious water entering (as vapor) from the ground-level convergence. The updraft-core diameter is a few kilometers.



Cloud-Radiation Interactions in Climate Modeling and Remote Sensing

The Challenge: Reduce Uncertainty from Clouds in Global and Regional Climate Models

Clouds are one of the most poorly understood parts of the climate system even though their impact on global heating and cooling is far stronger than aerosols, and as great as, if not greater than, all anthropogenically created or boosted greenhouse gases. Only water vapor surpasses clouds, which are just liquid or ice water particles small enough to not precipitate but large enough to scatter and absorb sunlight and thermal radiation. To complicate the issue, man-made aerosols (e.g., pollution, biomass burning) can modify cloud optical properties for scattering (reflection back to space) and absorption (atmospheric heating and re-emission). Anthropogenic particulates can also alter cloud life cycles, including the suppression of rain in some regions.



Above: Cloud opacity forces light to bounce randomly. Tenuous regions inside clouds, gaps between clouds and cloud layers enable very large jumps, making the diffusion process “anomalous.” Statistics for the total length of the convoluted photon paths from top-of-atmosphere to ground support the anomalous diffusion model.

Los Alamos Innovation: Breaking Away from the Conventional "Slab-Cloud" Model

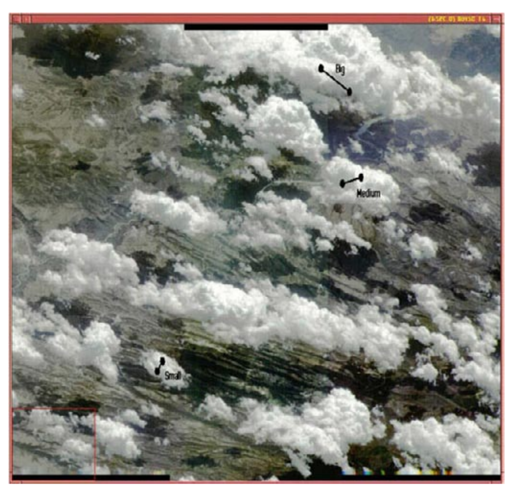
Clouds can be investigated from below (using radiometers and/or lasers), from within (primarily using aircraft), or from above (especially using space assets with imaging capability). They are so variable in space and time that there is never enough data, especially of the *in-situ* kind that we trust the most. Satellite remote sensing brings the greatest expectations. However, the algorithms used to infer cloud properties from observed radiances as well as the energy balance computations for climate modeling depend on radiative transfer theory. In essentially all such operational settings, this theory is predicated on the unrealistic assumption that clouds are infinite, uniform slabs because that geometry is historically perceived as the only tractable case. At Los Alamos, we have developed new radiative transfer models targeting either the radiative energy budget or remote cloud diagnostics that account for the 3-D variability of clouds. Our innovative observation methods are both passive (sunlight-based) or active (laser-based) as in the case of Wide-Angle Imaging Lidar. The new radiative energy partition models are by design amenable to the contrasting situations where we know either very little or a lot about 3-D cloud variability, all depending on the scales of interest.

Below: Broken clouds (from DOE’s high-resolution Multispectral Thermal Imager satellite) not amenable to the standard “slab” model used in remote sensing. Our finite-cloud algorithm uses reflected and transmitted radiance and gives good results for the three indicated cases with different sizes.

The Impact: Eliminating Biases in Cloud and Climate Dynamics, Renewing Cloud Remote Sensing

The hallmark of cloud radiative transfer modeling at Los Alamos is to go beyond the use of 3-D theory to quantify the error in standard methodology, which typically ignores all cloud variability inside a satellite’s cloudy pixels or inside a climate model’s grid cells. We propose effective mitigation strategies. For instance, we have developed

- 3-D remote sensing methods specifically for broken or isolated clouds (see lower figure);
- “Off-beam” lidar systems that can penetrate opaque clouds using scattered laser photons;
- An efficient physics-based method for estimating heating and cooling at every point inside a 3-D cloud as it is dynamically modeled;
- An anomalous diffusion model for the mean radiative fluxes through the whole atmospheric column (see upper figure).



This last model has successfully explained the variability of new photon path length observations using oxygen-line spectroscopy at very high resolution.

Los Alamos NATIONAL LABORATORY

Producing Fuel and Managing Waste with Oceanic Gas Hydrates

The Challenge: Developing New, Non-Polluting Energy Resources

The countries of the world currently burn the equivalent of 60 billion barrels of fossil fuel per year, emitting seven billion tons of carbon in the form of CO_2 into the atmosphere. The atmospheric CO_2 concentration has increased from 280 ppmv (parts per million by volume) in the year 1800 to 370 ppmv in 2000. This increase is closely linked to global climate change. Energy consumption and CO_2 emissions continue to increase each year. As the largest energy consumer in the world, the United States relies on fossil fuel imports to make up its 20% shortage in energy production. Such reliance on foreign resources is not conducive to national energy security. These two issues—climate change and reduced reliance on foreign energy sources—will most likely dominate future energy planning.

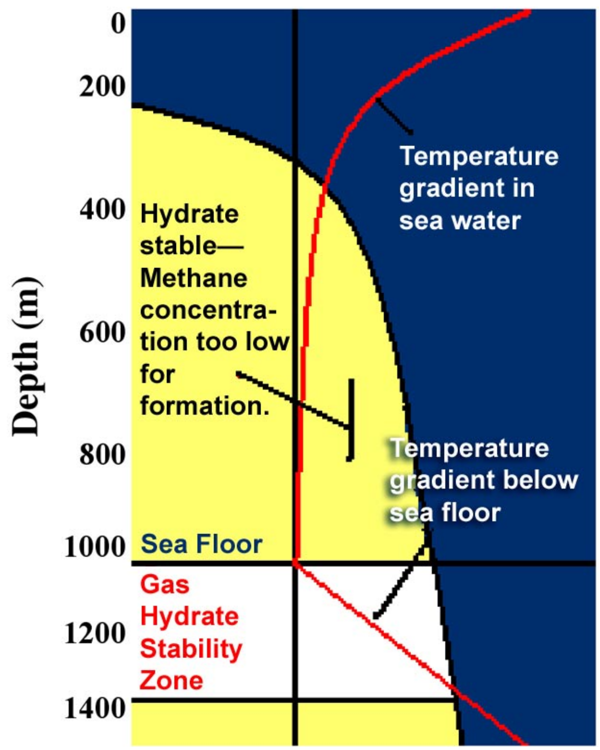
Los Alamos Innovation: A Viable Strategy for Using Methane Hydrates

Over the last two decades, ocean exploration has uncovered a new fuel source—methane hydrates. Methane hydrates are usually found in ocean sediments on the sea floor of continental shelves or slopes (at a depth range of 350 m to 1200 m). The molecular structure is similar to ice except a methane molecule is trapped within the hexagon cage of ice. Methane hydrates exist in meta-stable equilibrium with their environment and are affected by changes in pressure and temperature. When it dissociates, due to either lowering pressure or rising temperature, the methane gas escapes and the ice cage melts. The chemical energy stored in methane hydrates is estimated to be twice that of all other fossil fuels combined. The technology to mine this new resource is not currently available, but Los Alamos is working on a viable strategy to use methane hydrates as a fuel source. The general proprietary design is a "closed system" (that is, no pollution byproducts will be emitted from the fuel cycle). While the concept requires additional refinement and investigation before being made available for marketing, the Laboratory anticipates looking for partners interested in engineering design studies in the near future.

The Impact: National Energy Independence and Reduced Greenhouse Gas Emissions

A methane hydrate closed energy cycle would reduce U.S. dependence on foreign energy supplies and help control the primary culprit in global warming—greenhouse gas emissions.

Methane hydrate phase boundary (the half bell-shaped curve) and the sea water temperature profile (red line). Based on this temperature profile, it is possible to find methane hydrates on the sea floor at a 400 m depth. The methane concentration affects the actual depth where hydrates can be found (or mined).



Los Alamos NATIONAL LABORATORY

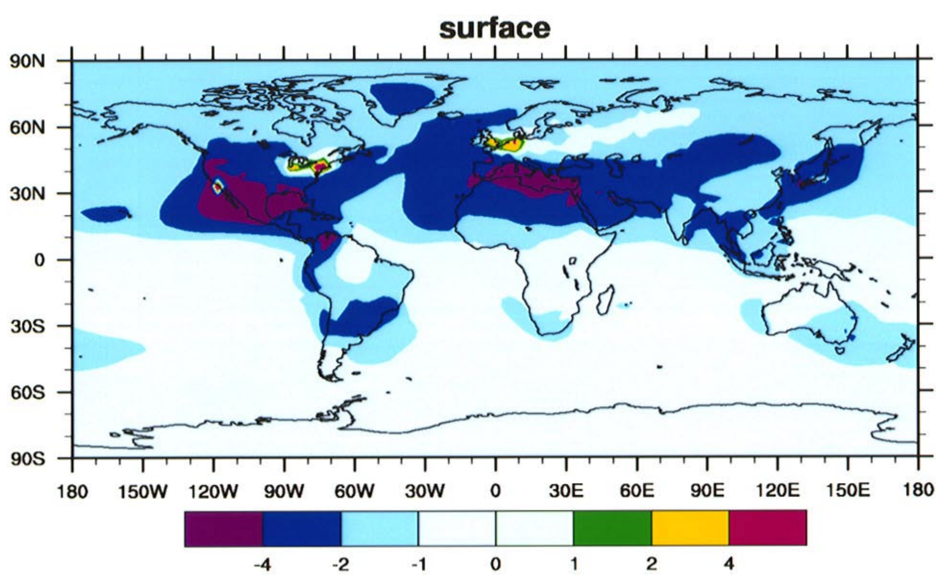
Environmental Benefits and Risks of a Hydrogen Economy

The Challenge: Preparing for Risks Posed by Transition to a Hydrogen Economy

Hydrogen is likely to play a prominent role in delivering non-polluting energy to society. Hydrogen fuel cell technologies deliver high efficiency and their large-scale implementation promises to benefit human health by enhancing urban and regional air quality. Hydrogen could also reduce risks of climate change if its large-scale production by renewable or nuclear energy sources becomes viable. While it is well known that the byproduct of energy produced from hydrogen is water vapor, it is not well known that the storage and transfer of hydrogen is inevitably accompanied by measurable leakages of hydrogen. Unintended consequences of hydrogen leakage include a reduction in global oxidative capacity, and an increase in stratospheric water that could exacerbate halogen-induced ozone losses as well as impact the Earth's radiation budget and climate. An environmental risk-benefit analysis is clearly needed to guide policy for, and guide the development of, a hydrogen economy.

Los Alamos Innovation: Using a Global Atmospheric Model to Study Hydrogen Economy Scenarios

Los Alamos is using a global atmospheric model to examine the impacts of various hydrogen economy developments and leak scenarios on atmospheric chemistry. We are focusing on the effects of a reduction of nitrogen oxides from switching to fuel cells, as well as leaks from the production, distribution, and use of hydrogen. These include the improvement of air quality on a regional scale and a reduction of global oxidative capacity. We are also examining the increase in stratospheric water and its potential for increasing halocarbon-induced ozone levels there.



Global model calculations of reductions in tropospheric ozone (smog) in parts per billion if we switch the power and transportation sector from fossil fuels to hydrogen thereby eliminating the emissions of nitrogen oxides and hydrocarbons.

The Impact: Defining Tolerable Leak Rates for a Hydrogen Economy

Los Alamos's environmental risk-benefit analysis will define environmentally tolerable leak rates for a global hydrogen economy and provide a proactive approach to implementing new energy technologies in the 21st century.

New Approaches in Numerical Methods for Climate Modeling

The Challenge: Developing Accurate Numerical Climate Models

Numerical modeling is essential for understanding human impact on climate, but climate simulations intrinsically contain errors that could prevent accurate assessments. Contributing factors include imperfect knowledge of physical processes and numerical errors due to discretization of continuum equations. Even perfect models of physical processes can produce incorrect or misleading results when discretization errors are not controlled. Hence, it is important to understand and minimize the role discretization errors play. Climate simulations are routinely run for millions of time steps and thus significant build-up of time discretization errors can occur during a given simulation. Also, climate simulations typically employ very coarse spatial resolution and hence spatial discretization errors could be as large or larger than the temporal errors. Unfortunately, because current climate models do not monitor either type of discretization error, the impact of these errors on climate model predictions cannot be assessed.

Another important source of error present in current climate models is that they all employ a time splitting or "divide and conquer" approach to solving their nonlinear physics packages. This approach can destroy natural force balances present in climate regimes. For example, by splitting fluid dynamics calculations from those related to cloud processes, large-scale balances produced by this interaction could be significantly altered.

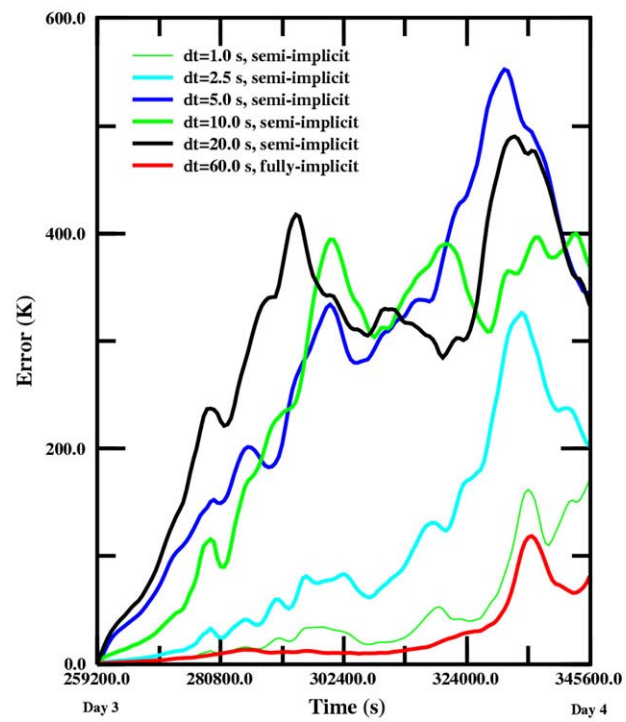
Los Alamos Innovation: Combining Nonlinear Solution Procedures with Time Stepping Approaches

To quantify the magnitude of time splitting errors in climate simulations, new numerical frameworks must be developed. A numerical framework currently being tested involves the use of a nonlinear solution procedure, the Jacobian-Free Newton-Krylov approach (JFNK). When combined with higher-order Runge-Kutta time stepping approaches, the JFNK procedure is able to monitor both the evolution of temporal errors and to adapt the time step size to minimize their impact on a simulation.

The figure to the right shows a first attempt to quantify the time splitting error for a simulation relevant to atmospheric science, a three-dimensional idealized hurricane simulation. Even in this relatively simple problem run for a short time period, the temporal error growth in simulations employing decoupled physics packages is considerably larger than from a simulation employing a coupled physics package.

Another problem with traditional numerical approaches is that they do not converge the nonlinearities associated with the different physical processes, so these approaches can readily miss important time scales in the problem with the result that the accuracy of their forecasts is significantly degraded. The JFNK solution procedure can help determine whether time-scales in physics packages are being violated by lack of convergence of the nonlinear solver.

Errors in an idealized 3-D hurricane simulation, using decoupled and fully-coupled methods (JFNK approach). The fully-coupled method uses the largest time step but still has the smallest error. The error grows over time in all simulations.



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